Th. Sect

"SOME ASPECTS OF THE J PHENOMENON IN X-RAYS."

Thesis for the degree of Ph.D.

in the University of Edinburgh

by

William H. Watson, M.A.

June 1925.

The J-phenomenon in X-rays has been the subject of experimental investigation in the Physical Laboratory of the University of Edinburgh during the last ten years. In this period Barkla has evolved a systematic account of many of the facts of what appears to be one of the most important discoveries in connection with electromagnetic radiation. Only recently has it been possible to summarise with any true sense of perspective the conclusions drawn from many hundreds of experiments. Accounts of these conclusions are to be found in 'Nature', Nov. 22, 1924, and in the Philosophical Magazine, May 1925, p.1033. In the latter communication at p.1034 Barkla describes the early investigations which led to the comprehensive attack on the puzzling results of these early experiments.

The resemblance of the J-phenomenon to the phenomenon of X-ray K, L, M fluorescence is very marked and led to the naming of the new phenomenon. For, in the J-phenomenon, "as a primary radiation of increasing frequency passed through a substance, while there was in general the usual diminution in absorption, at the critical penetrating power there occurred :

(1) a sudden increase in the absorption of the primary X-radiation;

(2) a sudden increase in the ionisation in the substance when that substance was in the gaseous state;

(3) an increase in the electronic emission from the substance when that was a solid in the form of a thin plate; and

(4) in the immediate neighbourhood of this critical frequency there appeared from the substance a secondary radiation more absorbable

than the primary". (Barkla, loc. cit. p. 1035).

There are however many features which distinguish the J-phenomenon from the phenomenon of X-ray fluorescence - or, indeed, from anything previously known. The most striking features are:-

"1. The phenomenon is conditional on some factor or factors which have never previously been considered as a governing factor in X-ray phenomena. The only condition essential to X-ray fluorescence and the accompanying K, L, or M absorption phenomenon is (as far as has been discovered) that the radiation should possess some constituent frequency greater than the critical absorption frequency (Stokes' Law).

2. The sudden changes in absorption occur with surprising abruptness; indeed there appears to be an absolute discontinuity as though every constituent of the radiation being absorbed were suddenly absorbed at a higher level. In fact, the discontinuity in absorption appears to be quite as perfect when a heterogeneous beam is used as when the most homogeneous radiation is employed. Thus, if the constituents were independent, the rise in absorption would be very gradual, occurring for each constituent as it passed the critical absorption frequency.

3. The discontinuity is much more closely associated with an absorption coefficient than with a certain wavelength. According to all present conceptions, the filtered radiation contains the same constituents as the unfiltered, though in different proportions; yet frequently only the filtered radiation

shows the discontinuity. Change in intensity (alone and of the magnitude produced by filtering) has not been found to produce the result; it is due to change in the properties of the radiation produced by transmission through matter.

4. When the rise in absorption has occurred in a substance, the transmitted radiation is found to be more absorbable in other substances quite independently of the fact that these other substances exhibit their own absorption discontinuity (increased absorption). Thus the transmitted radiation is a transformed radiation as far as its penetrating power is concerned.

5. The change of critical absorption coefficient with atomic number of the absorbing substance is very small and diminishes with increasing atomic number.

6. The series of critical absorption coefficients in the various elements cut right across the well-known K series:" (pp.1053-4 loc. cit.)

The above quotations present the main features of the J-phenomenon without prejudice to the gradual development of new ideas based on later experimental work. The fundamental difficulty of investigation of the J-phenomenon has been, and still is, to discover an experiment or experiments which will give the same results for all similar experimental arrangements.* Should the controlling factors be found to be definitely outside the scope of experimental control there still remains the statistical method of investigation, from the results of the application of which it may be possible to arrive inductively at exact laws. It is not yet

* i.e.—alternative results under apparently similar conditions should be impossible.

proposed to adopt this method, for it is found that by employing the simplest possible methods of investigation, the number of results possible in any one type of experiment is so small and the differentiation between these results so marked, that it is difficult to doubt the operation of critical conditions which must, sooner or later, be revealed.

How critical are these conditions is constantly forced on the attention of research workers on this problem. The discontinuous relation between the intensity of one beam of X-rays relative to that of another from the same source, and the thickness of absorbing matter traversed, may be observed for long periods and yet without any traceable alteration in conditions, the discontinuity will disappear and give place to a continuous relation. The transition from the discontinuous to the continuous relation and vice versa, is sometimes observed in the course of a single series of observations and the differentiation between the two relations easily detected.

The process of adapting experimental method to the search for controlling conditions has been a long and tedious one, guided by the physical interpretation of the results of experiments which did not yield unique answers. It has been found necessary gradually to put aside many of the accepted ideas concerning X-radiation, and in particular that of the mutual independence - as regards quantum actions - of the monochromatic constituents of a "white" X-radiation.

The only alternative to the discarding of the latter most important principle in the theory of radiation, is the accepting of one of the earliest conceptions evolved in connection with the J-absorption phenomenon. According to this idea, it was assumed that the constituents of all wavelengths in a heterogeneous beam experienced the "J" increase in absorption on account of a change in the "state" of the absorbing substance. This change of "state" was supposed to be induced by the incidence of radiation on the matter and to persist only so long as a particular combination of rays was superposed on the absorber. Experiments were made by the writer* to test directly this hypothesis, but failed to yield an answer.

On other grounds the conception of "state" of the absorber was particularly attractive. The so-called transformed aluminium was observed to absorb X-rays to the same extent as "untransformed" silicon, which element has an atomic number greater by one than that of aluminium. This fact suggested that in the atomic nucleus there took place an action which was the counterpart to that observed in the spark spectra of ionised elements ("enhanced" lines).

Many experiments were made before the idea of "state" of absorbing matter was given up. The writer, in the course of making measurements of the absorption of primary beams by aluminium was led again to test this conception because of the appearance of what seemed to be fatigue in the so-called transformed aluminium. New sheets of aluminium were cut and numbered: these were substituted for aluminium sheets which had already been used in many

---

*Proc. Roy. Soc. Edin. XLV (I) p. 48

experiments. Systematic interchange of the different sheets was carried through, measurement of their term of exposure to the rays made, and their history recorded. Some sheets were subjected to great physical change - being heated till the metal became soft, and then allowed to cool. Observations showed that the appearance or non-appearance of the J absorption phenomenon could not be ascribed to changes in the aluminium alone. There is evidence from experiments by other workers which leads to the same general conclusion stated by Barkla, p. 1053 - "The critical condition appears to be provided either by the X-radiation or by something with the X-radiation, or by some external influence superposed upon the radiation."

Even while we are ignorant of the exact nature of these conditions we cannot, from the theoretical point of view, fail to notice the importance of following consequences of the facts of the J-phenomenon.

"There are alternative absorptions possible for what are <u>to all appearance</u> - i.e. from close examination by other methods - identical radiations. Corresponding to these alternative absorptions there are alternative corpuscular emissions and alternative ionisations in the substances exposed to the X-rays. Indeed the actions of X-rays (which means the quantum actions, for the actions referred to are governed by quantum laws) depend upon factors other than wavelength and the atomic number of the substance traversed. In other words, the activity of an X-radiation is dependent on factors which have hitherto not been taken into consideration ....

.....The photoelectric effect of X-rays of a given wavelength is not proportional to intensity, other factors are operative. In fact, experiments seem to show that as far as the J phenomenon is concerned the penetrating power of a complex radiation is a much more fundamental quantity than the wavelengths of its constituents. The phenomenon appears to suggest the separation of the quantum actions of radiation from the frequency of radiation". (p. 1055).

On account of the remarkably critical influence of absorbability of the radiation exhibiting the J phenomenon - the X radiation from any source, (whether an X-ray tube, a scattering radiator or fluorescent radiator) shows the phenomenon of "coherence". Two light rays from the same source are capable of interfering when subjected to suitable optical processes. "These rays are not, in the meaning of probability, independent of each other, for the oscillations of one ray are to some extent determined with those of the other."* Thus a certain degree of coherence is necessary in order that interference may take place. This property of coherence applied to monchromatic radiation is involved in phase relationships. There appears in connection with X radiation at least, and probably with all types of electromagnetic radiation under suitable conditions, a coherence of rays from the same source with respect to frequency - energy relationships. One type of such coherence is exhibited, for instance, by black body radiation, the interaction of which with matter is determined by temperature.

In fact we are led from a consideration of the J phenomenon to the position that rays of different frequency composing a heterogeneous X-radiation are not mutually independent. Under certain

---

* Planck "A survey of Physics" p 29, 1925.

conditions the ordinary laws of X-ray absorption do not describe the facts, and we cannot say the amount of energy transmitted through a distance x of matter is given by the expression

$$I_x = \int_0^{\nu_{max}} f(\nu)\, e^{-\left(\frac{\mu}{\rho}\right)\rho x}\, d\nu$$

where $f(\nu)$ is the energy distribution function of the radiation before transmission and $\left(\frac{\mu}{\rho}\right)$ is the mass absorption coefficient of monochromatic rays of frequency ν. Barkla has pointed out also that the fundamental assumption of the mutual independence and K, L, and M, ~~&c.~~ fluorescent absorptions will have similarly to be greatly modified.

Moreover, just as in the optical case definite phase relationship is the function in terms of which the coherence of different monochromatic rays from the same source is expressed, so in the case of X-rays which are coherent there must be an analogous function which expresses that coherence. It is difficult to define this function exactly, but there can be no doubt it is related to the quantum actions of radiation, for the coherence property it is designed to express is exhibited essentially in the quantum processes of the interaction between radiation and matter.

It is evident from the qualitative definition just given, and from the optical analogy, that it is the variation of this coherence function in the propagation of the X-radiation through matter which produces the energy discontinuities and apparent wavelength changes (J-transformation) which are the fundamental facts of the J-phenomenon. Whereas the changes involved in the phase function of monochromatic light rays are continuous - being concerned with the wave motion aspect of the radiation, those involved in the coherence function for X-radiation are discontinuous in character for they are concerned with discontinuous quantum actions. The J phenomenon is therefore the phenomenon of quantum "interference".

The importance of the superposition of X-rays has been pointed out by C.T.R. Wilson and with his earlier superposition experiments in mind the writer was brought, under the guidance of Professor Barkla, to look for absorption effects corresponding to Wilson's observations. These experiments are described in the second part of the paper referred to.*

This series of experiments was followed by an examination of the absorption of K series characteristic radiation by aluminium and copper with the object once more of testing superposition effects whenever any of the J absorption effects appeared.

While, as the results of these experiments show, we have failed to demonstrate the absorption effects of superposition when the superposed beams are proceeding in different directions, there is much evidence from other sources that superposition of rays proceeding in the same direction in the absorbing matter leads to the J phenomenon when certain critical conditions obtain.

Indeed it is probable that the real reason for the failure of the writer to observe the absorption effects of superposition was due, during the first series of experiments, to our failure to control the J critical conditions, and in the second series to the absence of coherence between the beams under examination.

* Watson, Proc. Roy. Soc. Edin. (XLV).

II. EXPERIMENTAL

The experiments to be described fall into two main groups (1) experiments on the absorption of superposed X-rays (2) experiments on the absorption of characteristic X-rays of K series by aluminium, and copper.

The former were recorded in the paper already quoted and a copy of this paper is included here for the account of the experiments.

The object of the second group of experiments has been indicated. The investigation was of the same type as that carried out with heterogeneous beams by Barkla and White and others in the investigation of the J phenomenon. The radiations employed were the characteristic rays of K series from the elements Ce, Ba, I, Sb, Sn, Cd, Ag, Rh, Mo, Zr and Sr. In addition to their being less heterogeneous than the radiation employed by Barkla, the characteristic rays are of wavelengths independent of the tube used to produce them.

The use of the observations to determine the absorption coefficients in Al and Cu of the homogeneous component radiations of K series is described below and a comparison is instituted between the results obtained here and those of other observers. (III Discussion of Results)

MEASUREMENT OF ABSORPTION

In order that we might test the effect of crossing the absorbing matter with a primary beam whenever any of the absorption

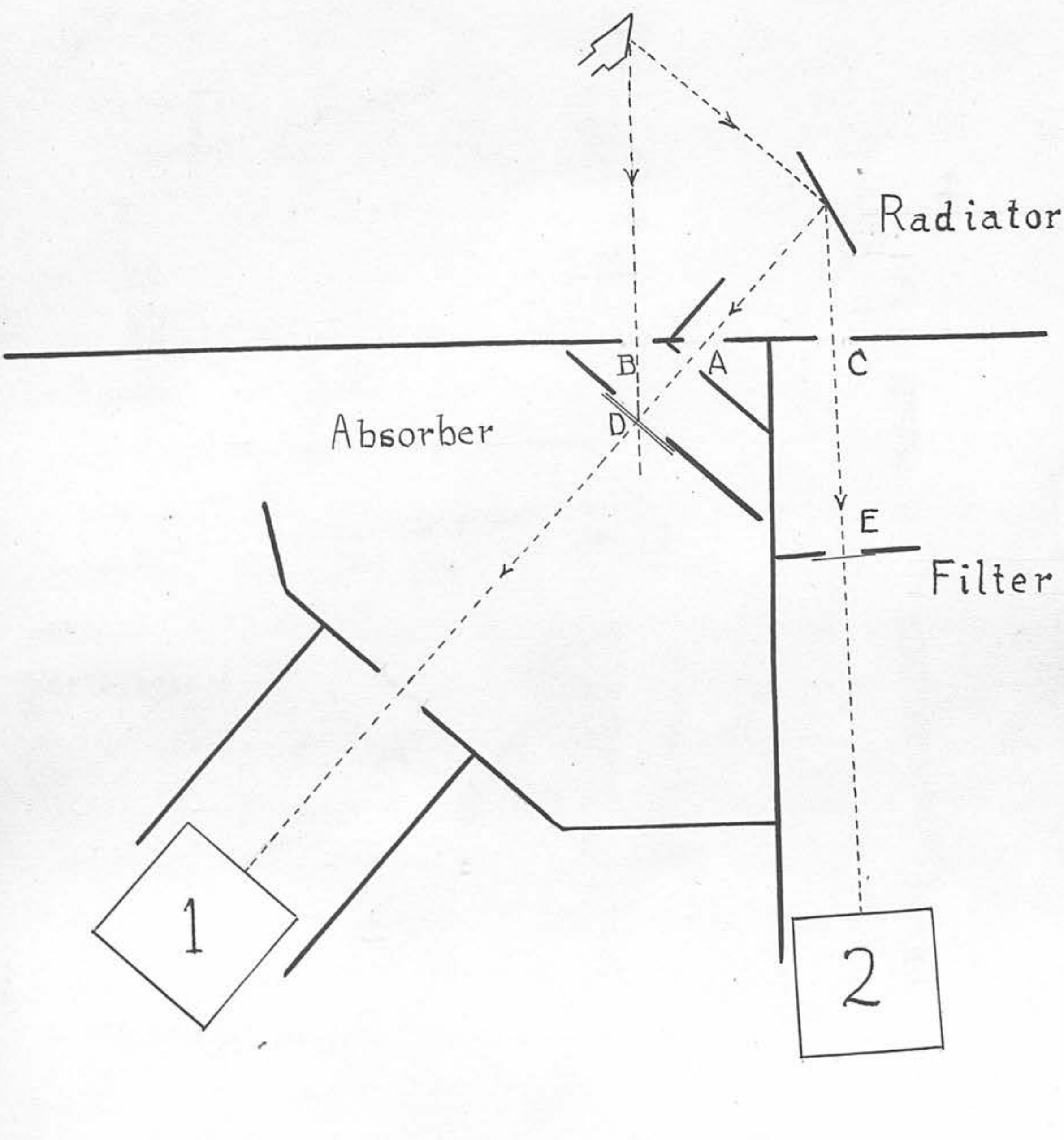


FIGURE I.

effects associated with the J phenomenon appeared, the arrangement of apparatus for these observations was the same as in recent experiments on the absorption of superposed X-radiations, and is shown in Fig. I

Through each of the apertures A and C (4 cms diameter) there passed a beam of the secondary radiation produced in a certain radiator by the incidence on it of a primary beam from a gas tube operated by induction coil with mercury-gas break. These secondary beams entered air ionisation chambers 1 and 2, where Wilson tilted electroscopes were employed to measure intensity. The sensitivity was about 10 divisions to the volt, and the potential difference required to produce the observed deflection of the leaf was measured after each reading: the relative intensity of 1 with respect to 2 was taken as the ratio of the potential increases in the corresponding electroscopes. The absorption of the beam A whose path was parallel to the axis of the X-ray tube was examined by measuring the intensity of ionisation in chamber I relative to that in 2 as successive thicknesses of absorber were placed at D normal to the rays 25 cms. from the anticathode of the tube. The aperture B served, when it was so desired, to allow a primary beam to fall on the absorber at D simultaneously with the passage of the beam A through the absorber.

A list of the radiators employed is given in the table below; they were placed in turn in the position indicated in fig. I. In those cases where powdered materials were used, a paste of the powder and 'seccotine' free from heavy substances was made, spread over an aluminium sheet and allowed to dry. The plate so formed was supported in a frame made of aluminium.

TABLE I.

Element	Radiator.
Sr	Carbonate (powdered)
Zr	oxide (powdered)
Mo	ammonium molybdate (powdered)
Rh	metal sheet
Ag	" "
Cd	metal (powdered)
Sn	metal sheet
Sb	oxide (powdered)
I	potassium iodide (small crystals)
Ba	carbonate (powdered)
Ce	ceria (powdered)

In all cases the radiator was of sufficient thickness to ensure nearly complete absorption of the primary radiation by the radiator.

The gas tube which supplied the rays incident on the radiator whose characteristic K radiation was to be investigated, was in each case manipulated until the most efficient production of characteristic rays was achieved. In this way, and owing to the partial polarisation of the primary, together with the fact that the path of the secondary beam for examination was parallel to the axis of the tube, the proportion of hard scattered secondary radiation was reduced to a minimum. Soft radiation scattered from the radiator in the direction of the beam under examination was largely eliminated by the passage of the beams 1 and 2 through aluminium filters of thickness appropriate to the quality of the characteristic beam. These filters were placed normal to the rays at apertures A and E.

In the measurement of absorption by copper, tests were made to ascertain if appreciable amounts of secondary Cu K radiation entered the ionisation chamber 1 from the absorber at D. A sheet of aluminium sufficiently thick to extinguish 99 per cent of Cu K radiation, but insufficient to cause sensible absorption of the other transmitted radiation, was placed just before the ionisation chamber 1. The difference in the values of I_x/I_0 with and without this absorbing sheet was practically negligible. (I_x is the amount of energy (relative to standard) transmitted through thickness x of absorber placed at D). We concluded, therefore, that no appreciable amount of secondary Cu K radiation entered electroscope 1.

The aluminium employed was of density 2·7 and contained 0·4 per cent iron as impurity. The copper, of density 8·93, was supplied rolled in sheets about 3·5 in. square: mean thicknesses were determined by weighing.

The measurements of I_x for different values of x, both for aluminium and copper absorbers, were recorded, one determination of I_0 in each series being made to obtain the corresponding values of I_x/I_0. This single determination of I_0 was a mean value determined at the beginning of a series of determinations of I_x. The error in I_x/I_0 introduced by assuming I_0 constant throughout a series is, of course, the same as that introduced by making determinations of I_0 contemporaneous with those of I_x: there follows the advantage of a much smaller interval between readings for different values of x, and of a shorter period for the measurement of a series. The maximum possible error in a single determination of I_x was in general about 1 per cent, but in the case of very small values of I_x it was as high as 4 per cent.

For homogeneous rays the law of absorption is

$$I_x = I_0 \; e^{-\left(\frac{\mu}{\rho}\right)\rho x}$$

where ρ = density of absorbing matter

$\frac{\mu}{\rho}$ = mass absorption coefficient of the rays under observation, in that matter.

This law holds up to a point even when the radiation is not homogeneous, provided the wavelength range for the components is not great.

When log I_x/I_0 had been plotted against x, graphs were obtained, which, except in the cases of absorption of Sn and Sb K radiations by Al, could be repeated and which were substantially rectilinear up to 80 per cent absorption in every case and in most cases when greater fractions were absorbed. Average values of log I_x/I_0 were then plotted against x and from the slopes of the lines, absorption coefficients of the filtered K radiations from the elements Ce, Ba, Sb*, Sn*, Cd, Ag, Rh, Mo, Zr, Sr, were obtained for absorption by Al and Cu. The probable error in the value of $\frac{\mu}{\rho}$, determined in this way, after allowing for all sources of error, is not greater than 2 per cent in any case. Assuming that the radiation examined consisted entirely of the K series characteristic

---

* Values in the case of Cu only were determined by this means for these elements.

radiation from the above elements in turn, i.e. that the proportion of radiation scattered from the radiator was negligible, we can determine to a first approximation the respective mass absorption coefficients of the α and β components of the series in Al and Cu in the following manner.

Siegbahn* gives as the relative intensities of the components of the K series, the numbers:

α_1 100 α_2 50 β_1 25 β_2 4.

Roughly, $\alpha : \beta :: 5 : 1$ if we assume only two components.

Let us denote by A and B the respective mass absorption coefficients of the α and β components in aluminium.

If a cms. is the thickness of the aluminium filter interposed in the path of the rays whose absorption is subsequently examined, then

$$\frac{I_x}{I_0} = \frac{e^{-A\rho(a+x)} + \cdot 2\, e^{-B\rho(x+a)}}{e^{-A\rho a} + \cdot 2\, e^{-B\rho a}}$$

Now the experimental results show that within the limits of error

$$\log_e \left(\frac{I_x}{I_0}\right) = -\left(\frac{\mu}{\rho}\right)\rho x.$$

where $\frac{\mu}{\rho}$ is the observed mass absorption coefficient. Hence if we approximate in the above expression for I/I_0 as far as x we obtain

$$\left(\frac{\mu}{\rho}\right) = A - \frac{A - B}{1 + 5e^{(A-B)\rho a}}$$

or

$$A = \left(\frac{\mu}{\rho}\right) + \frac{A - B}{1 + 5\, e^{(A-B)\rho a}}$$

In order to determine A, we have to find (A-B), which enters in the correction to be applied to $\frac{\mu}{\rho}$. A fairly good approximation to A-B may be obtained from a graph of $\frac{\mu}{\rho}$ against λ_α^3 where λ_α is the

* Spektroskopie der Rontgenstrahlen 1923, pp. 96 - 97.

wavelength of the K α_2 line, if we put A-B = the difference between the values of $\frac{\mu}{\rho}$ corresponding to λ_α and λ_β where λ_β is the wavelength of K_β. Knowing A and (A-B) we can of course determine B, and thus obtain absorption coefficients of approximately homogeneous rays whose wavelength is known from spectrographic work. The table III shows the calculation and the resulting values of A and B, the values for Cu being determined in a similar manner.

In order to illustrate to what extent the approximation employed is valid, let us examine the case of Ag K series radiation absorbed by aluminium after passing through ·046 cm. Al. The mass absorption coefficients of the two components of silver K radiation obtained by the method described here are 2·61 and 1·84 respectively. The following table II shows the results of calculation of $\log_{10} I_x/I_0$ together with the observed values. The calculated values are obtained employing the values quoted.

Table II

x (cms. al)	$\log_{10} I_x/I_0$ Calculated.	Observed
·046	$\bar{1}$·867	$\bar{1}$·868
·092	$\bar{1}$·735	$\bar{1}$·737
·138	$\bar{1}$·603	$\bar{1}$·610
·184	$\bar{1}$·472	$\bar{1}$·454
·230	$\bar{1}$·340	$\bar{1}$·329

When the calculated values were plotted $(\frac{\mu}{\rho})_{Al}$ was found to be 2·45, whereas the observed value was 2·47. In this case, the agreement is seen to be quite good, and we may reasonably expect equally good approximation in the other cases.

TABLE III.

Radiator K series	$(\frac{\mu}{\rho})$	a (cms Al)	A–B from graph	$(A-B)\rho a$ e	Total correction	A	B
			I. Absorption in Al				
Sr	8·70	·018	2·55	1·13	·47	9·17	6·52
Zr	6·30	·018	1·83	1·10	·32	6·62	4·79
Mo	4·74	·046	1·39	1·19	·27	5·01	3·62
Rh	3·16	·046	·97	1·13	·18	3·34	2·37
Ag	2·47	·046	·77	1·10	·14	2·61	1·84
Cd	2·15	·046	·64	1·08	·11	2·26	1·62
Sn	(1·63)	·046	(·52)	(1·07)	·09	(1·72)	(1·20)
Sb	(1·42)	·046	(·42)	(1·06)	·07	(1·49)	(1·07)
I	1·19	·092	·34	1·08	·06	1·25	·91
Ba	·84	·138	·27	1·10	·05	·89	·62
Ce	·68	·138	·20	1·08	·04	·72	·52
			II. Absorption in Cu.				
Sr	78·6	·018	20·2	1·13	3·7	82·3	62·1
Zr	59·8	·018	15·0	1·10	2·7	62·5	47·5
Mo	46·0	·046	12·9	1·19	2·5	48·5	35·6
Rh	31·5	·046	9·4	1·13	1·7	33·2	23·8
Ag	24·2	·046	7·5	1·10	1·4	26·6	19·1
Cd	21·4	·046	6·7	1·08	1·2	22·6	15·9
Sn	16·2	·046	5·5	1·07*	1·0	17·2	11·7
Sb	14·3	·046	4·5	1·06*	·8	15·1	10·6
I	11·5	·092	3·7	1·08	·7	12·2	8·5
Ba	7·9	·138	2·8	1·10	·5	8·4	5·6
Ce	6·2	·138	2·0	1·08	·4	6·6	4·6

* This value was obtained by extrapolation.

It has been pointed out that the results obtained in the absorption of Sn and Sb radiations by aluminium were by no means regular, nor, in general, capable of repetition as those in other cases were. The observations of the absorption of Sn and Sb radiations in aluminium and of Sn radiation in copper are given below in tables V and VI. It is quite evident from the regularity of the results obtained with copper absorbers that the variations obtained with aluminium absorbers are not to be attributed to variations in the character of the rays which could be detected in copper.

The difficulty in repeating observations with Sn and Sb radiations in aluminium rendered it unwise to make any deductions from particular series of observations. It appeared, however, that a change in the state of the aluminium absorbing the rays might be responsible for the variations in absorption (see recent results on superposed X-radiations loc. cit.) and that the appropriate condition for maximum absorption might be achieved by crossing the aluminium with a filtered primary beam. Accordingly, this was tested by the method of Part I, but no effect was observed; the agreement of scattering in the former case) was very good. The capricious variation in absorption also led to a trial of the effect of a weak magnetic field on absorption but no difference due to the field was detected.

In the case of Sn K radiation for which a large number of observation of absorption by aluminium was made, the value of $(\frac{\mu}{\rho})_{Al}$ appearing most frequently was about 1·63. This is employed in calculation in the table III. It gives values consistent with those for I, Ba, and Ce K radiations in the relation $(\frac{\mu}{\rho})_{Al}$ against λ^3. The corresponding value for Sb K radiation was observed but not so frequently.

TABLE V.

Absorption of Sn K Radiation.

Expt.	$(\frac{\mu}{\rho})_{Al}$	$(\frac{\mu}{\rho})_{Cu}$	Remarks.
1	1·77	16·3	Results in Al irregular.
2	1·79	16·0	A good straight line in Al up to 35% absorption
3	1·60	–	" " " " " " " 50% "
4	1·65	–	Straight 80% absorption
5	1·64	–	" " "
6	1·60	16·2	" " "
7	1·76	16·5	" 70% "
8	1·65	16·3	" 80% "
9	1·72*	16·2	*Initial slope in Al: slight hardening indicated on Filtering, but Cu results give a straight line.
10	1·77	–	
11	1·67	16·2	Straight in Al except for one value
12	1·72	–	Straight in Al
13	1·60	–	" " "
14	1·64	–	" " "
15) 16)	1·81	–	Two values of I/I_0: irregular.
17	1·60	–	Slight hardening indicated, otherwise regular.
18	1·64	–	I/I_0 for greater values of x not in agreement with straight line.
19	1·64	–	do.
20	1·66	16·0	Both Cu and Al show curvature due to harder radiation
21	1·65*	16·5*	*Initial slope in both cases: sudden change both in Al and Cu at $\log_{10} I/I_0 = 1·5$
22	1·59	16·3	do.
23	1·64	16·0	Slight hardening indicated
24	1·65	–	Straight except perhaps duality at x = ·276 cm. in Al.
25	1·62	–	do.
26	1·69	–	Straight line
27	1·64	–	" " except two values
28	1·65	–	" "
29	–	–	Too irregular for a determination of $(\frac{\mu}{\rho})$
30	1·67	–	Irregular: 3 values showing bad disagreement with straight line relation.
31	1·67	–	Straight line.

TABLE VI.

Absorption of Sb K Radiation

$(\frac{\mu}{\rho})_{Al}$	$(\frac{\mu}{\rho})_{Cu}$	Remarks.
1·58	14·6	
1·47	-	
1·48*	14·1	*Initial slope only
1·55	14·6	
1·55*	-	*Initial slope only
1·48	-	
1·42	14·2	
1·52	14·7	
1·47	14·1	

The values of $(\frac{\mu}{\rho})_{Al}$ and $(\frac{\mu}{\rho})_{Cu}$ for Sb and Sn K radiations have been calculated by combining in the same manner as in Table II the absorption coefficients of the two homogeneous components of the K series obtained from the observations of Richtmyer and Allen on homogeneous rays. It will be noticed that the agreement as shown in Table VII is good in the case of copper and that the calculated values for $(\frac{\mu}{\rho})_{Al}$ agree with the less frequent observation by myself of high values of $(\frac{\mu}{\rho})_{Al}$ both for Sb and Sn K radiations.

TABLE VII

Radiator K series	$(\frac{\mu}{\rho})_{Al}$ (calculated)			$(\frac{\mu}{\rho})_{Al}$ observed	$(\frac{\mu}{\rho})_{Cu}$ calculated		$(\frac{\mu}{\rho})_{Cu}$ observed
	Richtmyer	Allen	Watson	Watson	Richtmyer & Allen	Watson	Watson
Sn	1·74	1·78	(1·74) 1·64	1·60 to 1·79	16·8	16·6	16·2
Sb	1·54	1·61	(1·52) (1·45)	1·42 to ~~1·48~~ 1·58	14·9	14·4	14·3

Regarding the absorption of Sn K radiation by aluminium some early results of Bragg and Porter (Proc. Roy. Soc. A, 85, p. 355, 1911) are worthy of notice; they were not obtained in experiments carried out specially for the measurement of absorption coefficients. The value of $(\frac{\mu}{\rho})_{Al}$ for Sn K radiation was obtained as 1·83 while Barkla & Collier (Phil. Mag. 23, 1912) obtained 1·57. It is not surprising that the values obtained by these different observers differ from each other, but that the difference between their respective values should be so great, is remarkable. From an examination of the conditions of experiment one would expect the value of Bragg & Porter to be at least as low as that of Barkla & Collier, for the former used a tin box instead of a sheet as radiator, with consequently greater filtering out of the softer component in Sn K radiation.

Whether or not these results can be reconciled in terms of the known laws of absorption for X-rays, the higher value seems to be confirmed by some results recorded by the writer measuring $(\frac{\mu}{\rho})_{Al}$ for Sn K rays, in a test of the quality of radiation emitted from a tin plate exposed to rays from a gas tube, under conditions different from those obtaining in the series of absorption measurements described above. The absorption coefficient was determined by 50 per cent absorption and gave $(\frac{\mu}{\rho})_{Al}$:

1·77, 1·81, 1·87, 1·77, 1·74, 1·80.

It is important to note that these readings were obtained over a period in which the hardness of the tube was varied in the intervals between successive determinations and that the rays were filtered by ·046 cm. Al. Other measurements of a like character made by the writer gave the following values.

Radiator K series	$(\frac{\mu}{\rho})_{Al.}$	$(\frac{\mu}{\rho})_{Cu}$	$(\frac{\mu}{\rho})_{Ag.}$
Sn	1·84	-	13·7
"	1·77	-	14·3
"	1·80*	17·3*	-
Sb	1·58	-	49·9
"	1·57	-	47·2
"	1·51*	14·5*	-

* These values were obtained in the course of preliminary tests on the series Ce - Sr.

In the course of experiments, it was found necessary to replace the 12 in. coil, in use at first, by a 10 in. coil. The same tube was employed but the speed of rotation in the mercury gas break was changed. Although the values obtained in other cases (including $(\frac{\mu}{\rho})$Cu for Sn K rays) were unaltered by this change, those of $(\frac{\mu}{\rho})$Al for Sn K rays were generally less with the latter coil than with the former. It is doubtful, however, whether this observation is of real significance.

A further scrutiny of the results of Bragg and Porter (loc. cit) reveals evidence of some additional effect in aluminium not present in the absorption of Sn K rays by Fe, Ni, Cu, Sn, Zn. These observers measured the ratio

$$\frac{\text{Emergence cathode rays (energy)}}{\text{Incidence} \quad " \quad " \quad (\; " \;)}$$

for plates of Al, Fe, Ni, Cu, Zn, and Sn, on which Sn K rays were incident, and they obtained the values :

Al	Fe	Ni	Cu	Zu	Sn
1·80	1·50	1·50	1·50	1·50	1·36

Bragg and Porter were disposed to ignore the difference in the case of Al; it is probable, however, in the light of other results, particularly those of Wilson* that this difference is further evidence of the abnormalities in X-ray absorption by aluminium, which are associated with this region of the spectrum, i.e. of the J phenomenon.

* Proc. Roy. Soc. (A) CIV pp. 1-23 and 190-212

III. DISCUSSION OF RESULTS AND COMPARISON OF THEM WITH THOSE OF OTHER OBSERVERS.

The absorption coefficients of homogeneous X-rays, of wavelength determined by crystal reflection, have been measured in aluminium and in copper by the following observers over the range of wavelength specified in each case.

(a) Hull & Rice: In Al from •392 to •147 A.U., and in Cu from •294 to •147 A.U.

(b) Williams: In Al and Cu from •431 to •627 A.U.

(c) Richtmyer: In Al from 1•054 to •130 A.U., and in Cu from •715 to •135 A.U.

(d) Hewlett. In Al from •861 to •130 A.U.; no observations in Cu.

(e) Duane & Mazumder: In Al and Cu from •165 to •095 A.U.

(f) Allen: In Al and Cu from •710- •110 A.U.

(g) Stoner & Martin: In Al and Cu from •30 to •708 A.U.

The results (a) (c) (d) (e) (f) (g) with those from the experiments here described have been plotted in graphs of $(\frac{\mu}{\rho})$Al and $(\frac{\mu}{\rho})$Cu respectively against λ^3 see Figs. II . The results of Williams shew so little agreement with those of the other observers that no useful purpose is served in including them.

---

1. Hull and Rice: Phys. Rev., 8, p. 326, 1916
2. Williams: Proc. Roy. Soc. A 94, p. 567, 1918
3. Richtmyer: Phys Rev. 18, p. 13, 1921
4. Hewlett: Phys. Rev. 17, p. 284, 1921
5. Duane & Mazumder: Proc. Nat. Acad. Sci:, March 1922
6. Allen: Phys. Rev. 24, p. 1, July 1924.
7. Stoner & Martin: Proc. Roy. Soc. A, 107, 1925.

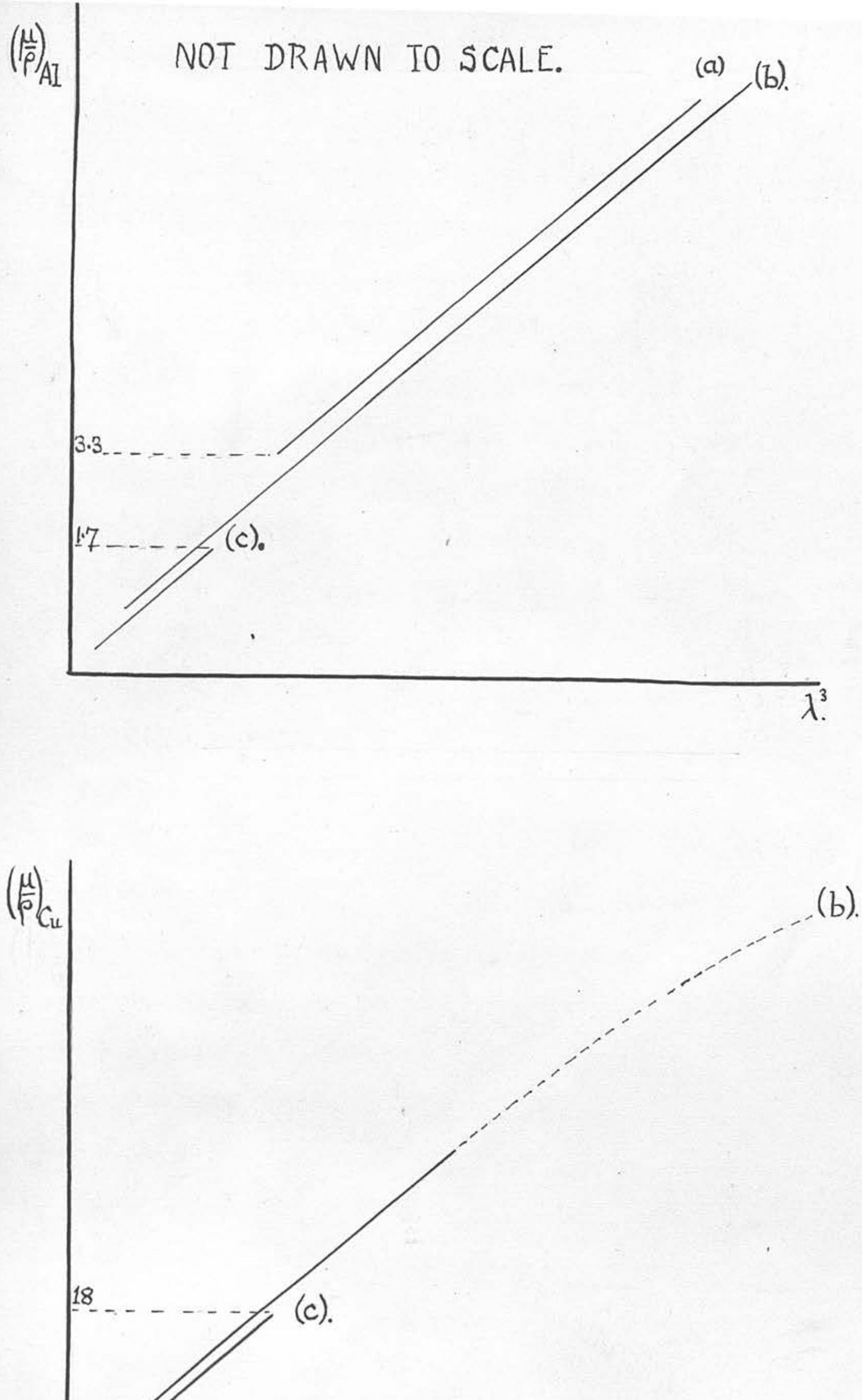

$\left(\frac{\mu}{\rho}\right)_{Al}$
NOT DRAWN TO SCALE.
(a)
(b).
3·3
1·7
(c).
λ^3
$\left(\frac{\mu}{\rho}\right)_{Cu}$
(b).
18
(c).
λ^3

FIGURE III.

Examination of the graphs shows that the values of $(\frac{\mu}{\rho})_{Al}$ and $(\frac{\mu}{\rho})_{Cu}$ obtained by these observers for different wavelengths are by no means so irregularly distibuted as one might conclude from a cursory glance. All the values for $(\frac{\mu}{\rho})$ seem, when plotted against λ^3, to lie on definite straight lines. There are <u>three</u> lines in the case of Al, and <u>two</u> in the case of Cu. For reference the lines are quoted on a separate diagram (fig. III). The observations belonging to these different groups are provided by the various observers as follows.

In Al:

(a) Richtmyer, Allen, Stoner & Martin and Hewlett.

(b) All observers including the writer.

(c) Hull & Rice, Hewlett, Watson.

In Cu.

(b) Richtmyer, Allen, Stoner& Martin, Duane & Mazumder, Watson.

(c) Stoner & Martin, Richtmyer, Hull & Rice, Watson.

It is clear that the evidence for none of these distinct relations between $(\frac{\mu}{\rho})$ and λ^3 is solely dependent on the work of a single observer, though any one observer's results might have been dealt with as deviating from a continuous relation on account of experimental error, if that were assumed to be greater than the accuracy claimed for the observations will allow. The grouping of results in the manner stated above seems to be the only method of establishing the mutual consistency of the observations of different experimenters over the range of wavelengths examined.

It will be noticed that the observations of the writer show the

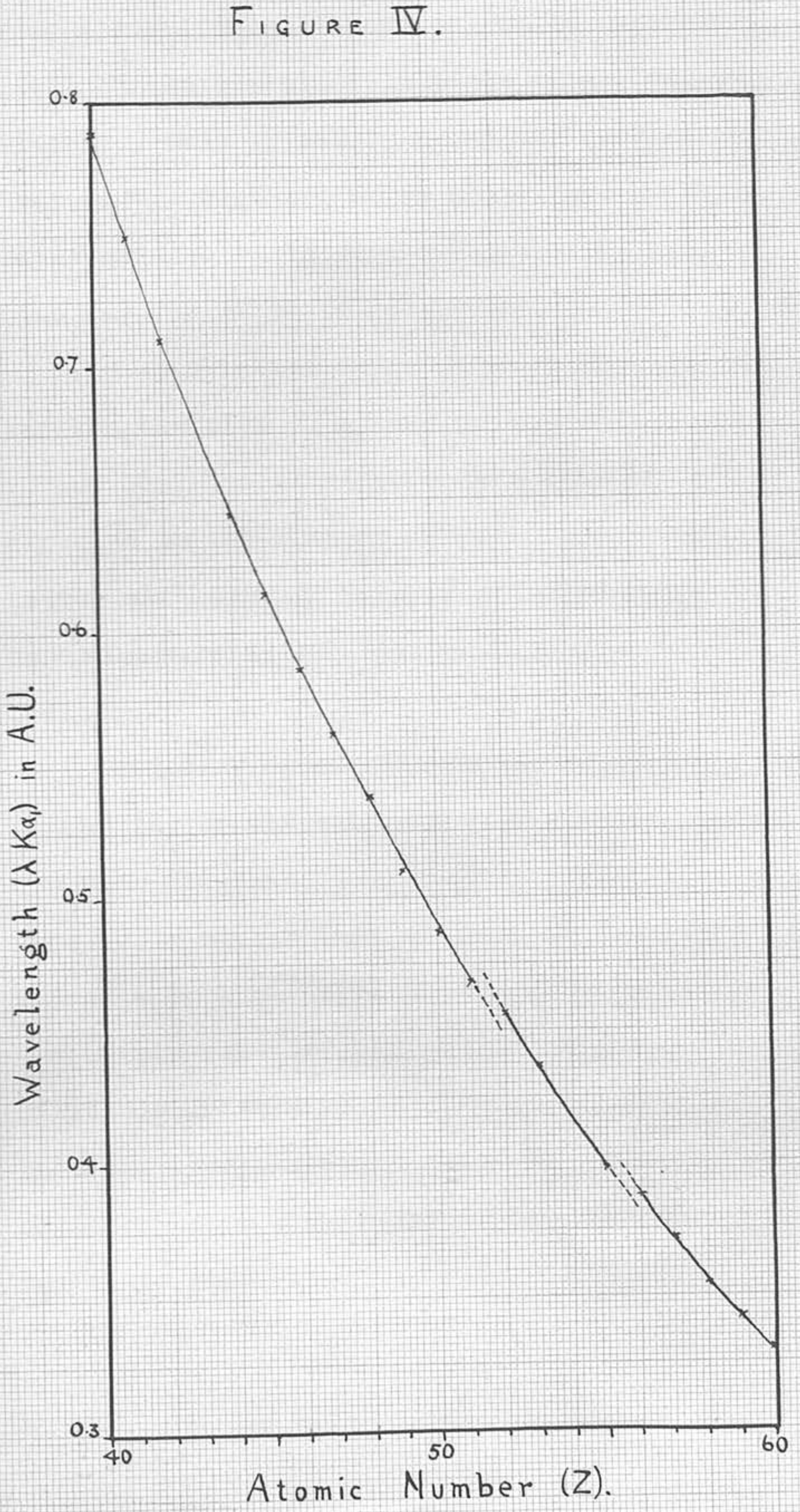


FIGURE IV.
0·8
0·7
0·6
0·5
0·4
0·3
Wavelength (λ Kα₁) in A.U.
40
50
60
Atomic Number (Z).

transition from (b) to (c) both in Al and Cu for the same wavelength. With a significant exception, to be referred to later, this transition can be explained in terms of an interesting and important discovery made by Khastgir and the writer described in a letter to 'Nature'* Further, as we shall see, it is in terms of similar ideas and the facts of the J-phenomenon that the occurrence of the line (a) for Al is to be explained.

In this letter it is pointed out that the relation between the wavelengths of K_{α_1}, α_2 and β_1 emission lines as given by Siegbahn** do not obey the continuous relation with atomic number which would be expected in the absence of the J phenomenon. Part of the text of the letter will explain clearly the nature of the deviations from the continuous relation between λK_{α_1} and Z, the atomic number of the radiator.

"Fig. IV... shows the variation of the wavelength $K\alpha$ with atomic number (Z) of the radiator from Z = 40 to Z = 60; the plotted values are from Siegbahn..... If we follow λ for $K\alpha$ as Z is increased from 40, we notice that at Z=52 and Z=56 there takes place a sudden increase in λ relative to the value which would have occurred were the simple relation for smaller atomic numbers obeyed. The magnitude of this excess is about 0·01 A.U. in each case. Exactly the same irregularities occur in $K\alpha_2$ and $K\beta$. Lack of data prevents any conclusion with regard to $K\gamma$. The degree of precision claimed for these spectroscopic observations is too high to admit of any

---

*'Nature' Apr. 25, 1925, p. 604, "Spectroscopic Evidence of "J phenomenon in X-rays.

** Jahrbuch der Radioactivität, 1916.

other conclusion than that these irregularities are real deviations from the simple law". Further, "one can only conclude that these irregularities are due to the J-transformation of X-radiation taking place in the calcite crystal used for the analysis of the radiation or possibly in the anticathode or walls of the X-ray tube".

It is obvious that the use of these wavelengths which correspond to the radiation after J transformation may introduce discontinuities in the relation between $(\frac{\mu}{\rho})$ and λ^3 discussed above, i.e. the wavelengths of the components α and β of the characteristic radiations of K series given by Siegbahn may not correspond to the radiations examined by absorption methods in our experiments.

With the exception of the values of $(\frac{\mu}{\rho})$ for Sn K radiation and Sb K radiation, the transition from the line (b) to (c) both in Al and Cu is so explained, i.e. by the fact that the radiation examined and the wavelengths assumed do not correspond. On the other hand the wavelength discontinuity at $Z = 56$ (Siegbahn) has no corresponding discontinuity in the relation between $(\frac{\mu}{\rho})$ and λ^3 either in Al or Cu, and we conclude that the K radiations of the elements Ce and Ba examined by absorption methods had been transformed in transmission through the radiator or in the Al filter employed.

Thus complications have been introduced in the relation between $\frac{\mu}{\rho}$ and λ^3 because of J transformation of the radiations used in the determination of λ and also because of the absence of transformation in some of the characteristic radiations in the absorption experiments. The cases of Sn and Sb characteristic radiations present a still more puzzling problem, but it is significant that here we are in close proximity to the J_2-level critical absorbability for the whole K radiation.

It appears, therefore, that the existence of the line (c) in the relation between $(\frac{\mu}{\rho})$ and λ^3 is associated with and explained by the J_2 absorption discontinuity and the fact of J transformation.

The line (a) in Al, it will be noticed, appears when $(\frac{\mu}{\rho})_{Al} > 3{\cdot}3$, and it is in this very region that the J_1 absorption level occurs.*
We can only conclude that the transition from (a) to (b) in the case of Al is due to the operation of J transformation which invalidates the correspondence between absorbability and wavelength.

The J phenomenon is the only experimental fact which can account for the results obtained not only by the writer - but by other workers not engaged in examining the phenomenon, and, in the case of Bragg and Porter, before the existence of the phenomenon was known.

* Barkla, Phil. Mag., May 1925, p. 1051.

IV. THE RELATION OF COMPTON'S "QUANTUM THEORY OF SCATTERING OF X-RAYS" TO THE J PHENOMENON

Compton's "Quantum Theory of Scattering of X-rays" derives its chief support from two types of experiment.

In the first place there are C.T.R. Wilson's observations by the photographic method on the ionisation of air by X-rays of wave-length less than 0·5 A.U. These experiments showed the appearance of short range β ray tracks in rough agreement with Compton's formulation, and on the other hand they bring to light features which are quite inexplicable apart from the development of the entirely new conceptions regarding the interaction of radiation and matter, to which the study of the J phenomenon is leading us.

Further support is derived from spectroscopic examination of the secondary radiation from light substances on which is incident a monochromatic radiation accompanied by a heterogeneous general radiation.

We have already seen that the results of these experiments are essentially part of the J phenomenon examined by different methods. According to the ideas of the J phenomenon* the "modified line" observed by Compton and others is produced by transformation of the secondary radiation in its passage through the radiator or through the crystal of the spectrometer. That the conception of transformation of the radiation in transmission and not in the process of scattering is essentially correct, has been shown by the

---

* Barkla: Nature, (Nov. 17, 1923
" (Nov. 22, 1924.

following facts : -

(1) primary beams of X-rays show this transformation

(2) the Compton "shift" can be made to take place after the secondary radiation has left the scatterer.

(3) energy discontinuities occur in the secondary radiation at the same critical penetrating powers as are observed in the J absorption phenomenon with primary rays.

But not only so; monochromatic primary rays have on examination by the spectroscope shown this same transformation. This was first pointed out in the letter "Spectroscopic Evidence of the J phenomenon" by Khastgir and Watson, to which reference has already been made and which has been quoted above.

In the light of this body of evidence of the transformation of X-rays of all kinds under suitable conditions, Compton's contention of quantum scattering of X-rays becomes quite untenable and there is little purpose here in dealing with the quantitative aspect of his theory which has given that theory an appearance of physical reality which a more fundamental examination of experimental facts must have shown to be illusory.

V. CONCLUSION.

Though many of the important facts concerning the J phenomenon are now known, lack of control of the critical conditions for J-absorption and J-transformation leads to complexity in the results obtained in the case of experiments where each of the quantities to be determined involves a number of different measurements. In many cases it becomes extremely difficult not only to interpret the results obtained in the measurement of absorption coefficients, but - as already pointed in connection with the examination of Sn K - radiation - even to assign a value to the absorption coefficient as ordinarily understood.

From this complexity we are impelled to return to the simplest possible methods of investigation. For example, to compare the quality of secondary radiation from light substances with that of the primary, the procedure now adopted in this laboratory is to determine the relative intensity of secondary to primary as successive equal thicknesses of absorber are interposed in the path of each beam. This method has now been adopted in the examination of the primary radiation from an X-ray tube in different directions about the cathode stream. It is in this investigation that the writer is at present engaged; and it is hoped that, by combining the results of it with those already known on the effect of the direction of the secondary (relative to the exciting primary radiation) on the appearance of the J absorption phenomenon in the secondary, it may be possible to get a better conception of the processes involved in the J phenomenon, and to determine the critical conditions necessary for the appearance of the phenomenon.

Further, concerning the use of the X ray spectrometer in these matters (apart from its aid as a means of providing homogeneous X-rays), it is necessary to insist that it is likely at this stage to be of very little help either in examining the physical processes involved or in elucidating the entirely new facts of the J phenomenon. The spectrometer is an instrument which examines the wave-motion aspect of radiation; the quantum aspect of the interaction between radiation and matter can only properly be examined by the measurement of quantum effects, as such. Finally, it is quite evident that, had spectroscopic methods alone been employed, the remarkable coherence property of X radiation observed in the J phenomenon would either have remained undiscovered or required ultimately for its investigation the very methods which have brought it to light.

COPY, without diagrams, of Letter to "Nature", April 25th 1925, p.604

"SPECTROSCOPIC EVIDENCE OF THE J-TRANSFORMATION OF X-RAYS"

by S.R. Khastgir and W.H. Watson.

(fig. I of the letter is quoted in section III above)

SPECTROSCOPIC EVIDENCE OF J-TRANSFORMATION OF X-RAYS.

The relation between the atomic number of a radiator and the wave-lengths of its X-ray emission spectrum of K-series is generally assumed to be the regular one desceibed by Sommerfeld's extension of Bohr's idea to X-ray spectra. Well-marked irregularities, however, have not received attention in the literature of the subject; it is the object of this note to direct attention to them.

Fig. 1 shows the variation of the wave-lengths $K\alpha_1$ and K_A (absorption limit) with atomic number (Z) of radiator from Z=40 to Z=60; the plotted values are from Siegbahn, and Blake and Duane respectively. Fig.2 is an enlargement of Fig.1, to show more clearly the irregularities which we shall proceed to describe. If we follow λ for $K\alpha_1$, as Z is increased from 40, we notice that at Z=52 and at Z=56 there takes place a sudden increase in λ relative to the value which would have occurred, were the simple relation for smaller atomic number obeyed. The magnitude of this excess is about 0·01 A.U. in each case. Exactly the same irregularities occur in $K\alpha_2$ and $K\beta$, but not in K_A. Lack of data prevents any definite conclusion with regard to $K\gamma$. The degree of precision claimed for these spectroscopic observations is too high to admit of any other conclusion than that these irregularities are real deviations from the simple law.

It is certainly no fortuitous coincidence that the wave-lengths at which these sudden increases take place, correspond very well with two of the critical absorbabilities for J-transformation, which in the case of aluminium are $(\mu/\rho)Al$ = 1·9 and 0·7 (see Bakerian Lecture by Barkla, Phil. Trans. 1917, and Barkla and White, Phil. Mag. 34, Oct. 1917), and are only very slightly displaced by change of the atomic number of the transmitting element when this is small. The atomic structure of the radiator cannot be supposed responsible for the irregularities referred to, for, at the atomic numbers indicated, there is no re-adjustment of electronic distribution according to the Bohr scheme. As there is no reason, either theoretical, or practical, for the occurrence of these irregularities, apart from the J-transformation, and as they appear precisely in the same place as in the experiments showing J-discontinuities, one can only conclude that these irregularities are due to the J-transformation of X-radiation taking place in the calcite crystal used for the analysis of the radiation or possibly in the anticathode or walls of the X-ray tube. We have, however, no information of the crystal used by Blake and Duane for the measurement of K_A.

This seems to be the first spectroscopic evidence of the J-transformation, which by absorption methods has been found in primary rays (Barkla, Silvanus Thompson Lecture, Nature, Nov. 22, 1924) and in scattered rays (Barkla and Khastgir, Phil. Mag. 49, Jan. 1925). This also strongly supports the view expressed by Barkla (Nature, Nov. 17, 1923, and Nov. 22, 1924) that the apparent increase of wave-length as observed by Compton and others in the scattered radiation is due to the same J-transformation during transmission in the crystal or in the radiator, and is not part of the phenomenon of scattering at all. That the magnitude of the change appearing in the curves shown here is of the order of the Compton shift, gives further support to this contention. It must be understood, however, that the attainment of a critical wave-length is not the only factor which determines whether or not the transformation takes place.

S.R. Khastgir
W.H. Watson.

Physical Laboratory,
University of Edinburgh.
March 27, 1925.

REPRINT FROM THE

PROCEEDINGS

OF THE

ROYAL SOCIETY OF EDINBURGH.

SESSION 1924–1925.

VOL. XLV—PART I—(No. 7).

An Investigation of the Absorption of Superposed X-radiations.

By Wm H. Watson, M.A.

EDINBURGH:
PUBLISHED BY ROBERT GRANT & SON, 126 PRINCES STREET, AND
WILLIAMS & NORGATE, LTD., 14 HENRIETTA STREET, COVENT GARDEN, LONDON, W.C.2.

MDCCCCXXV.

Price One Shilling.

VII.—An Investigation of the Absorption of Superposed X-radiations. By Wm. H. Watson, M.A. *Communicated* by Professor C. G. Barkla, F.R.S.

(MS. received February 4, 1925. Read March 9, 1925.)

The first experiments on this subject were suggested by the absorption effects associated with the "J" phenomenon. In a comparison of the absorbability in aluminium and in copper of the radiation emitted in one direction from an X-ray tube, it is found * that in many cases, as the tube is hardened and a certain value of the mass-absorption coefficient reached, there is a *sudden* increase in the absorption by aluminium. Since the radiation is not strictly homogeneous, and since the above effect does not invariably take place, it is evident that the phenomenon is not to be explained simply in terms of a "J" series characteristic radiation similar to K and L characteristic radiations as regards the manner of its excitation. It is evident that certain critical conditions must obtain before the phenomenon occurs, and on account of the abruptness of the change it appears as though the whole wave-length range of the radiation were affected in respect of absorption by aluminium. This seems to be further substantiated by the fact that the discontinuous character of the change in absorption is preserved with a beam which is much more heterogeneous. It is possible, therefore, that the attainment of the critical conditions results in a change in the absorbing properties of the aluminium. This change seemed, when the present experiments were initiated, to be adequately described by the statement that the aluminium, when exposed to radiation beyond a certain frequency, sometimes behaved as the element of next higher atomic number.

If the increase in absorption is due to some temporary transformation of the aluminium, we should expect an increase in the absorption of *another* beam of X-rays of different quality when passing through the transformed aluminium at the same time. We shall refer to a beam in which the critical conditions for such transformation are attained: *i.e.* one in which the additional absorption occurs, as an "effective beam," and one in which they are not attained as "ineffective." The assumption of transformation then leads us to expect that the incidence of an "effective" beam on

* Barkla, *Bakerian Lecture*, 1916; Barkla and White, *Phil. Mag.*, 34, 1917.

aluminium would increase the absorption, by that aluminium, of a second beam which by itself is "ineffective." The object of the first series of experiments was to find if this increase in absorption does take place.

[Provided no similar J absorption effect is produced in copper, and that the assumption of transformation is valid, the "ineffective" type of beam is such that its representative point in a graph of $\left(\frac{\mu}{\rho}\right)$ Al against $\left(\frac{\mu}{\rho}\right)$ Cu lies on the lower line of Barkla and White *; when both aluminium and copper show the change, the corresponding point lies approximately on the same line; the beam "effective" in Al only is represented by a point on the upper line.]

If an intermittent source of high potential be employed to generate X-rays in such an experiment as that suggested, it is necessary that the two superposed beams should be produced by the same source of high potential, otherwise actual superposition of the beams will not take place. Consideration of the complexity of apparatus which would be introduced by the use of two X-ray tubes led to the adoption of one tube to produce two beams for investigation, differences in character being brought about by the use of radiators and filters.

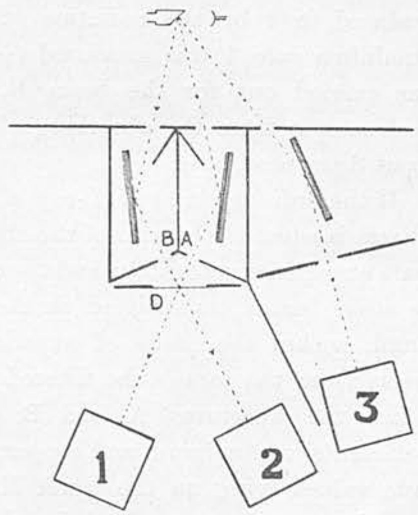


FIG. 1.

As the effect to be looked for was expected to be of the order of a 13 per cent. change in absorption coefficient, it was decided that a definite answer could be obtained if X-ray intensities were measured by ordinary gold-leaf electroscopes with air ionisation. The apparatus was arranged as in fig. 1, in which the heavy lines represent lead screens.

Through each of the circular apertures A, B (of 4 cm. diameter) there passed a beam of X-rays produced by the scattering of a primary beam from an ordinary gas tube (Pt anticathode) operated by induction coil with mercury-gas break. The scattering in each case took place from a slab of aluminium 15 cm. square and 1·8 cm. thick. After having traversed filters specified below, these secondary beams proceeded to the electroscopes 1 and 2.

* Barkla and White, *Phil. Mag.*, 34, 1917.

A third scattered beam, produced in a similar fashion, entered electroscope 3. The ionisation current in this electroscope was used as a standard to which the ionisation currents in 1 and 2 were related. Lead screening was introduced where necessary to eliminate stray effects. The position (D) occupied by the aluminium sheets absorbing the rays is indicated in the diagram; the plane of the aluminium was equally inclined to the two beams.

The procedure was as follows:—The deflection (a) of the gold-leaf in electroscope 1 relative to 3 was determined with aperture B closed and A open; then with B and A open (β); finally, A was closed and the effect produced in 1 by the radiation of beam B scattered by the absorbing aluminium into 1 was measured (γ). A series of similar measurements was carried out for the beam B. By increasing the distances of the electroscopes from the absorbing aluminium, the effect γ was reduced to about 3 per cent. of a.

If the ordinary laws of X-ray absorption hold, the total absorption of a beam is equal to the sum of the absorptions which the components of the beam experience separately, and the absorption of such a beam is unaffected by other beams transmitted at the same time, *i.e.* $a=\beta-\gamma$. This was found, within the limits of experimental error, to be the case for two beams from the same tube filtered with different amounts of aluminium before the apertures A and B, when the respective mass-absorption coefficients in aluminium and copper, determined by 50 per cent. absorption, gave values lying on the lower line of Barkla and White (*i.e.* critical conditions were not attained for either beam).

The results in Table I are those in three typical experiments.

TABLE I.

Beam.		(1)		(2) $\left(\frac{\mu}{\rho}\right)$ Al. Cross Beam	
		$\left(\frac{\mu}{\rho}\right)$ Cu.	$\left(\frac{\mu}{\rho}\right)$ Al.	Off.	On.
1	A	7·1	·77	·78	·81
	B	9·0	1·04	1·02	1·05
2	A	6·3	·71	·75	·74
	B	8·5	·85	·82	·80
3	A	6·3	·64	·61	·63
	B	7·3	73	·74	·72

First $\left(\frac{\mu}{\rho}\right)$ Al and $\left(\frac{\mu}{\rho}\right)$ Cu were determined for the beams A and B, with the absorbing sheets placed normal to the path of the rays (col. 1). An amount of aluminium sufficient to cut down the intensity of A by half was then placed at D in position to transmit both beams (fig. 1). From measurements of α and $\beta-\gamma$, and a knowledge of the angles between the aluminium at D and beams A and B, $\left(\frac{\mu}{\rho}\right)$ Al in the cross-beam experiments was calculated. A few typical results are quoted in (2), Table I. The problem and ultimate difficulty of the experiments lay in the controlling of the beams A and B, so that while in one the critical "J" conditions had been obtained, they were not attained in the other.

It was known that the "J" conditions may be produced by transmission (see Barkla, *Nature*, November 22, 1924), and an attempt to achieve the required control of the beams was made by filtering B first with tin and in later experiments with barium carbonate, the elements Sn and Ba having absorption edges in the regions where the "J" discontinuities most frequently appear. These attempts proved unsuccessful, and on the one occasion when success appeared to have been attained the beam known at first to be "ineffective" was subsequently found to be "effective," having been rendered so, not by transmission, but in its genesis: transition to the effective type must have taken place just after the determination of the character of this beam. Thus were observed the two values of the absorption coefficient in Al corresponding to one value of the absorption coefficient in copper. In one the J absorption did not occur; in the other it did. The relative values of $\left(\frac{\mu}{\rho}\right)$ Al and $\left(\frac{\mu}{\rho}\right)$ Cu (Tables I and II) obtained here are not in complete agreement with those of Barkla and White, as it was not the intention in either set of experiments to obtain absolute values of a high degree of accuracy, but to examine the abrupt change; the fractional separation of the two groups of values of $\left(\frac{\mu}{\rho}\right)$ Al is, however, almost exactly the same as in the results of Barkla and White. Measurements were made in the case where both A and B were beams belonging to the upper line of Barkla and White, and no effect of superposition was observed; typical results are incorporated in Table II.

It will be seen that these experiments failed to answer the question which led to their being undertaken, because of the difficulty (as yet unsurmounted) of controlling critical conditions which are at present unknown. This lack of success led to the abandonment of further

TABLE II.

Beam.		(1)		(2) $\left(\frac{\mu}{\rho}\right)$ Al.	
		$\left(\frac{\mu}{\rho}\right)$ Cu.	$\left(\frac{\mu}{\rho}\right)$ Al.	Cross Beam Off.	Cross Beam On.
1	A	5·71	·73	·75	·75
	B	8·94	1·09	1·03	1·03
2	A	6·5	·78	·79	·81
	B	6·5	·78	·78	·81
3	A	4·43	·53	·51	·52
	B	* 6·31	·64	·74	·74

investigation until the publication of C. T. R. Wilson's "Cloud Photographs." †

These photographs show that when X-rays of wave-length less than 0·5 A.U. pass through air,‡ there are produced paired β-ray tracks having their origins very close together and in some cases at the same point. The pairs may be composed of members of the same class or one of each of the two classes of β-rays which such X-rays are capable of ejecting and which differ greatly in range (the difference in kinetic energy generally corresponds to more than 20,000 volts). Further, such paired tracks have *their origin practically without exception within the primary beam of X-rays.*

Wilson suggests that these phenomena may be explained on the assumption that an atom of nitrogen from which a K-electron, in the absence of other influences, cannot be ejected by a quantum of nitrogen K-radiation, may, when exposed to nitrogen K-radiation together with radiation of higher frequency, be able to absorb both radiations (with the ejection of a K-electron) much more readily than either separately. Wilson also suggests "that many features of the β-ray tracks, including the curvature which sometimes appears, may be due to radiations which are excited in atoms by the passage of the β-particle, the radiations continually overtaking the β-particle and affecting the nature of its

* Measurement of $\left(\frac{\mu}{\rho}\right)$ Al and $\left(\frac{\mu}{\rho}\right)$ Cu after the performance of the cross-beam experiment gave ·72 and 6·2 respectively; this is the case referred to above.

† C. T. R. Wilson, *Proc. Roy. Soc.* (A), vol. civ, pp. 1–23 and 190–212.

‡ It is in just this part of the spectrum that the additional J ionisation in air has been observed (Barkla, *loc. cit.*). Evidently Barkla and Wilson observed by different methods the same phenomenon.

collisions with electrons in atoms subsequently traversed" (p. 208, *loc. cit.*).

In the light of these observations it appeared to us to be probable that a solid element on which a sufficiently hard primary X-ray beam could be directed would absorb a second beam of X-rays characteristic of the element in question to a greater extent when the primary beam was incident than when it was not. It seemed possible, for example, that silver K-radiation falling on silver might be absorbed, when the primary cross-beam was in action, to about the same extent as Sb K-radiation. It was realised, of course, that in two important particulars the conditions holding in Wilson's experiments would not be reproduced in our experiments, where (i) the absorption took place in a solid instead of in a gas, and (ii) the primary radiation interacting with the characteristic radiation did not belong to that identical beam which had excited the characteristic radiation, as the two primary beams were emitted in different directions from the tube.

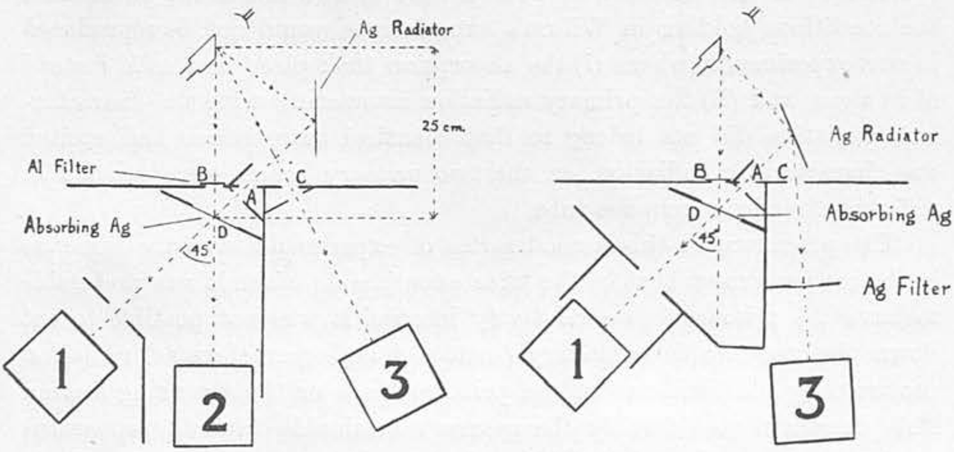
The procedure in this second series of experiments was the same as in the earlier, except that in the later experiments, since it was preferable to have the primary beam relatively intense, it was not possible to cut down the undesirable secondary (scattered and characteristic) radiation produced by the incidence of the primary beam on the absorbing matter. This decreased considerably the accuracy attainable with the apparatus employed, but, in view of the object of the experiments and the magnitude of the effect looked for, the loss of accuracy was not regarded, *a priori*, as serious.

In these experiments it is necessary to consider the selection of a proper standard relative to which measurement of X-ray intensities may be made. Since the electroscope (1 in fig. 2) which receives the approximately homogeneous Ag K-radiation receives also, when the primary beam is superposed on the absorbing silver, a heterogeneous secondary radiation, excited by this primary radiation, variation in the primary radiation from the tube may produce illusory effects. At first a heterogeneous primary beam filtered with aluminium was used to produce the standard ionisation: in some of the subsequent experiments a homogeneous Ag K-beam, filtered with aluminium, and in the remaining experiments filtered with silver, was used as standard (fig. 2, *b*).

In order to reduce to a minimum the amount of scattered radiation present with the Ag K-beam under examination, advantage was taken of the partial polarisation of the primary radiation incident on the radiator, by placing the axis of the X-ray tube parallel to AD (fig. 2, *a* and *b*).

A silver filter (·002 cm.) was placed in the aperture A. The intensity of the primary cross-beam was controlled by an aluminium filter placed before the aperture B. The beams A and B crossed in silver placed at D (25 cm. from the anticathode of the tube), and equally inclined to the two beams which made 45° with each other. The beams A and B entered electroscopes 1 and 2 respectively. Stray radiations were carefully tested for and eliminated.

In making the examination of the absorption of the Ag K-beam in silver, electroscope 1 was employed to measure relative X-ray intensities.



(*a*) Heterogeneous Primary Beam as Standard. (*b*) Ag K-Beam as Standard.

FIG. 2.

Let α = deflection in 1 relative to that in 3 with A open, B closed.

β = " " " A open, B open.

γ = " " " A closed B open.

$\beta-\gamma$ was compared with α, the result being expressed as the ratio $(\beta-\gamma)/\alpha$, which, according to the ordinary theory of X-ray absorption, should be equal to unity.

In each series of observations readings were made in the order $\alpha\beta\gamma$, $\gamma\beta\alpha$, $\alpha\beta$. . . . In this way it was hoped to eliminate systematic errors, and to minimise the effect of any changes in quality of the primary radiation. The accuracy of any determination of $\frac{\beta-\gamma}{\alpha}$ depends on the relative values of γ and α, being greatest when γ is small compared with α. For example, taking the comparatively large value which obtained in some of the experiments, and assuming the maximum possible error in α, β, γ to be 2–3 per cent., the maximum error expected in a single determination of $\frac{\beta-\gamma}{\alpha}$ is about 10 per cent. The error in the majority of experiments was, however, much less than this. Mean values were taken to reduce this error for a series.

A preliminary investigation was made to determine if any large effect takes place (*i.e.* $(\beta-\gamma)/\alpha$ differs greatly from 1) over a wide range of primary intensity. This was first carried out with small absorption of the silver characteristic radiation, and later with a 70 per cent. absorption. The results of the preliminary investigations are given in Table III.

TABLE III.

Al Filter in Primary Beam (B).	Thickness of Absorbing Silver.	$\frac{\gamma}{\alpha}$.	$\frac{\beta-\gamma}{\alpha}$.
1·8 cm.	·00135 cm.	·02	·994
1·8 "	"	·01	1·03
1·8 "	"	·02	1·003
·33 "	"	·25	1·039
·165 "	"	·40	1·029
·092 "	"	·45	1·028
·046 "	"	·58	1·027
·046 "	·00064 cm.	·27	1·050
·092 "	"	·24	1·052
·165 "	"	·20	1·020
·33 "	"	·15	1·004
1·8 "	"	·01	1·017

A pin-hole aperture at B was used in a test of the absorption of the primary beam when Ag K-radiation fell on the absorbing silver. No change was observed. The later results on the Ag K-beam are given in Table IV. In addition to Ag K-radiation, Sn, Sb, and Sr K-radiations were employed: of these, Sb K excites K-fluorescence in silver, Sn K does so only to a small extent, and the mass-absorption coefficient of Sr K-radiation in Ag is approximately equal to that of Sb K. The absorption of Ag K-radiation and finally of Ce K-radiation by aluminium, on which a primary beam was directed, was examined in the same way.

From Tables III and IV it is seen that in all cases the absorption of the secondary beam by aluminium was uninfluenced by the transmission through the absorbing substance of the primary cross-beam, although this was varied considerably both in its intensity and in its quality. It is worth noting that though the effect γ to be eliminated varied greatly from experiment to experiment, the corrected absorption

TABLE IV.

	Radiator.	Filter interposed in Primary (cm. Al).	Thickness of Absorber (cm.).	Absorbing Element.	$\frac{(\gamma)}{(\alpha)}$	No. of Determinations in Series.	$\frac{(\beta)-(\gamma)}{(\alpha)}$
A	Ag	·33 cm.	·00135	Ag	·23	4	1·043
	,,	,,	·006	,,	·89	7	1·052
	,,	,,	,,	,,	·88	7	1·038
	,,	1·12	,,	,,	·25	7	1·050
	,,	1·43	,,	,,	·16	7	1·018
	,,	·33	,,	,,	·93	5	1·004
	,,	,,	,,	,,	1·06	8	1·008
	,,	,,	,,	,,	1·25	9	1·052
	,,	,,	,,	,,	·83	6	1·038
	Sn	,,	,,	,,	·78	9	0·997
	Sb	,,	,,	,,	·44	5	1·018
	Ag	,,	,,	,,	1·04	5	1·093*
	,,	,,	,,	Al	·12	3	0·997
B	Ag	·33	·006	Ag	1·41 1·33	3 1	1·098 1·002 *
	,,	,,	,,	,,	1·44	9	1·016
	,,	·68	,,	,,	·82	7	1·022
	,,	·95	,,	,,	·57	6	1·013
C	Ag	·95	·006	Ag	·38	6	1·002
	,,	,,	,,	,,	·38	10	1·006
	,,	·33	,,	,,	·99	4	1·029
	,,	,,	,,	,,	1·00	12	1·039
	,,	,,	,,	,,	1·04	5	1·035
	,,	,,	·092	Al	·10	3	1·009
	Sb (K	·0013(Ag)	·0011	Ag	·35	11	0·988
	Sr (K)	0	·0011	Ag	·24	10	0·996
	Ce (K)	·33	·360	Al	·58	5	1·017

A, primary beam used as standard.
B, Ag K-beam as standard (filtered with Al).
C, Ag (Sb, Sr, Ce) K-beam as standard (filtered with ·006 cm. Ag).
The quantities (α), (β), (γ) are mean values for the number of determinations in the series given in column 6.

showed no dependence on this factor—a fact which indicates the reliability of the experimental results. (The type of standard employed did not influence appreciably the results obtained.) The secondary radiations employed were the characteristic radiations of the K series of Sr, Ag, Sn, Sb, and Ce; the last named was used because its penetrating power is in the neighbourhood of the J absorption in aluminium.

In the case of absorption of Ag K-radiation by silver, however, the only one on which a very large number of observations was made, there was found a general preponderance of values of $\frac{(\beta-\gamma)}{\alpha}$ in the neighbourhood of 1 and also of 1·04.

A statistical examination was made to test whether or not this grouping of the values is real, and also to find if a change of about 10 per cent. (increase in transmitted energy) indicated by the asterisked values in Table IV does occur more frequently than as a result of error.

Under conditions similar to those obtaining in the concluding experiments with silver reported in Table IV, a series of 120 determinations of the ratio of $\frac{\beta-\gamma}{\alpha}$ was carried through. The curve (fig. 3) shows the distribution of the values of the ratio obtained. It reveals two maxima—at ·99 and at 1·03—a grouping which was evident even in the course of tabulation of the values for the purpose of obtaining the distribution curve. There is no evidence of a peak at 1·10.

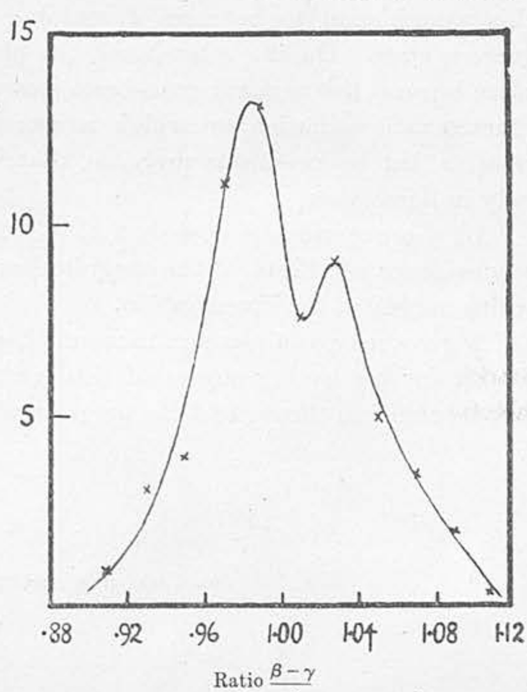


FIG. 3.—Ordinate: number of observations within the range 0·01 containing the value of the abscissa.

The mean value of the 120 observations is 1·011 midway between the peaks in fig. 3. This suggests the possibility of two effects nearly equally frequent in their occurrence: one in which there is no change in the amount of energy transmitted by the silver when a primary cross-beam is thrown on, and the other in which there is a 4 per cent. increase in the ionisation in electroscope 1 when a primary beam is thrown on at 45° to the Ag K-beam under observation. (The difference between ·99 and 1·0 has been neglected.)

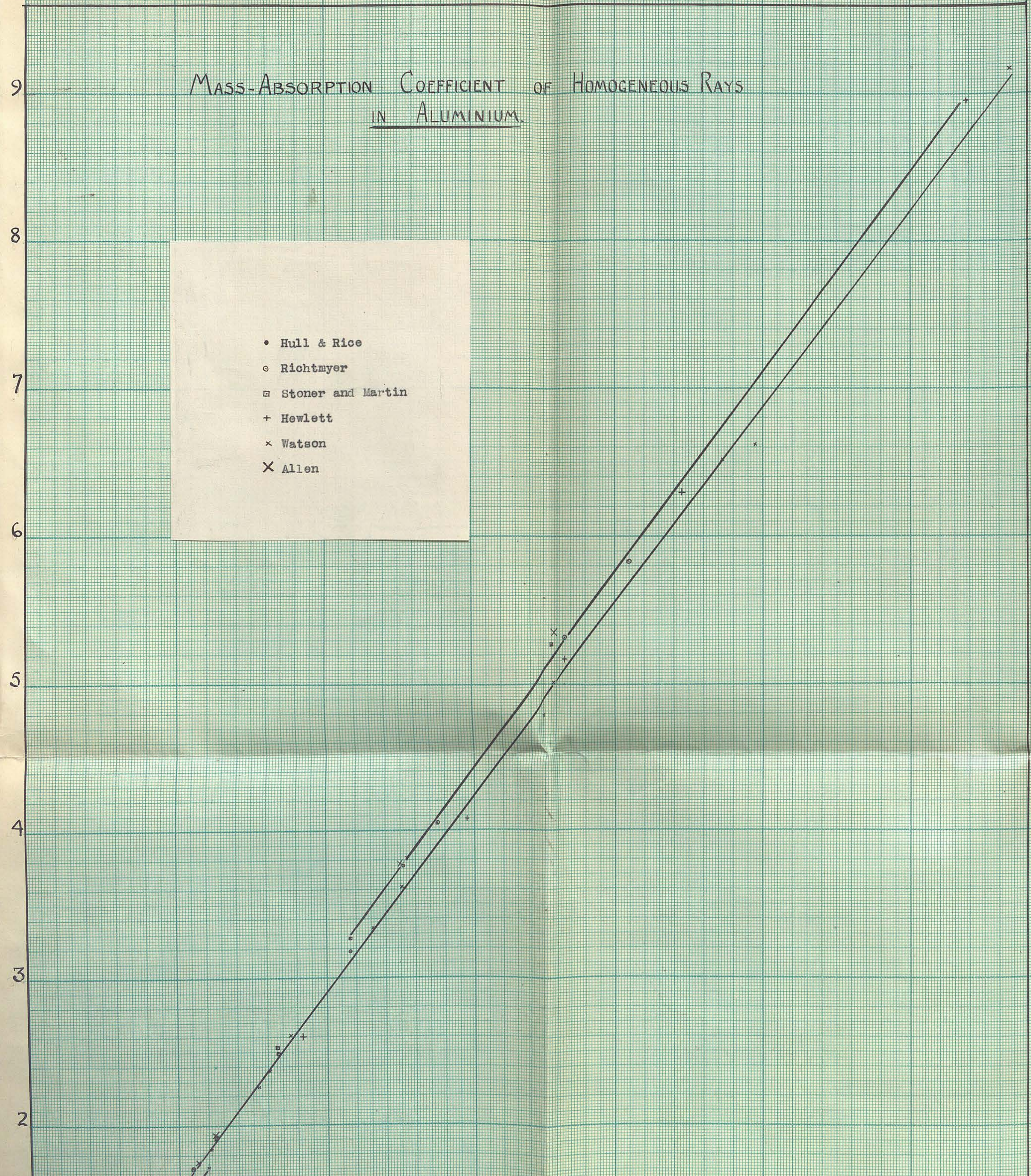
The evidence cannot be regarded as conclusive, and the effect is a small one, requiring fuller investigation before it will be possible to give an explanation in terms either of (1) an absorption fatigue effect in the silver, or of (2) a softening of the transmitted radiation so that the net effect is a 4 per cent. increase in the ionisation in the electroscope (since energy is measured in terms of the ionisation in a thin layer of air).

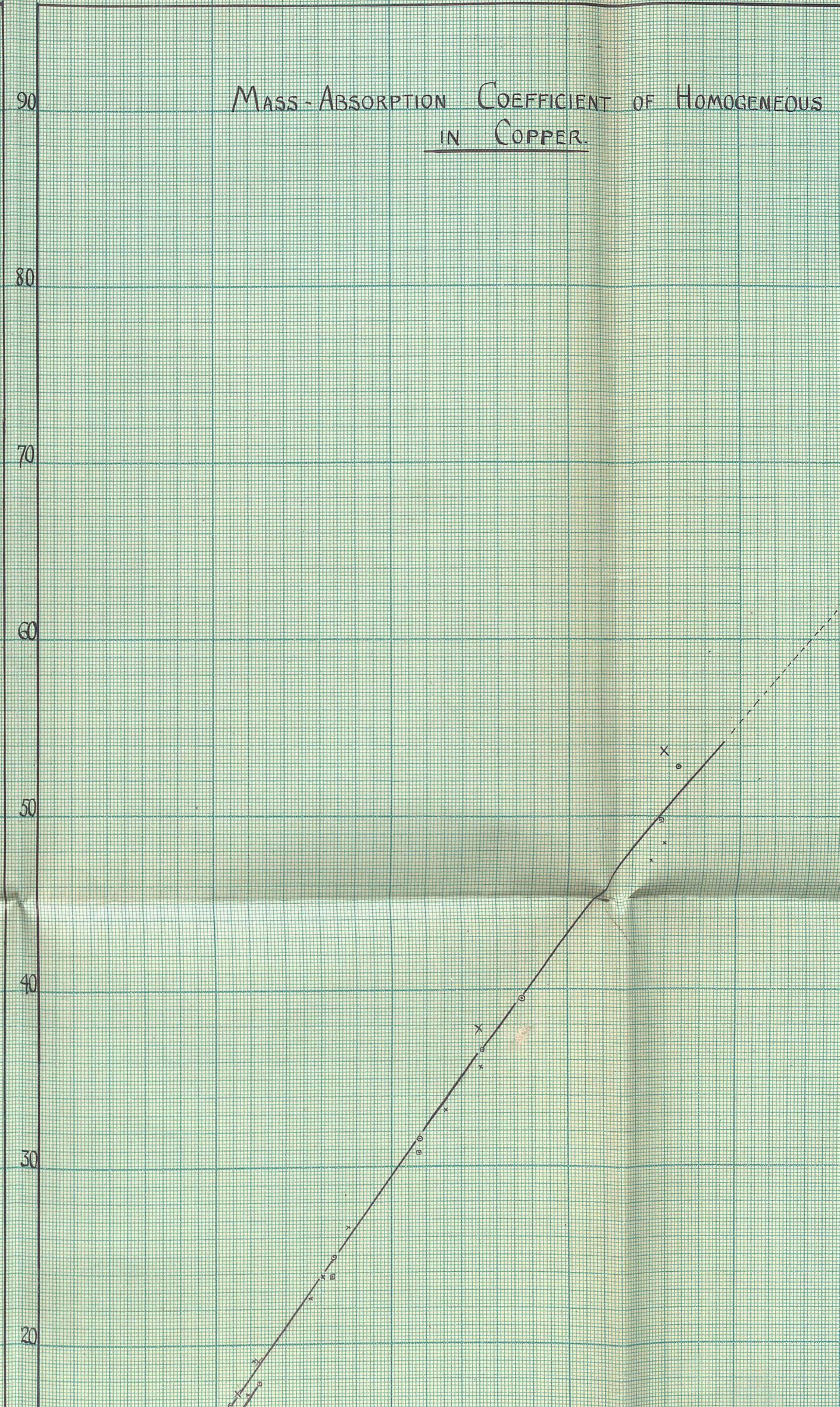
The experiments suggested by Wilson's photographs failed to yield the expected results, and if, as we have reason to believe, the primary beam was sufficiently penetrating, we are led to one or other of the following conclusions: (1) that the effect of superposed radiations on the electronic emission (observed by Wilson) does not appreciably affect the absorption. This might be because the additional electronic emission confined to the gas exposed to primary rays is due to accumulations of energy already absorbed and passed from atom to atom in the manner described by Wilson; (2) that Wilson's phenomena did not take place in these experiments. This might be due to the solid state of the absorber used here—though this would seem to be more favourable to the phenomenon than the gaseous state. On the other hand, the phenomena may not have taken place because the primary cross-beam was not that which had excited the characteristic radiation on which measurements were made. It is also possible, but by no means probable, that Wilson's phenomena take place only in light gases.

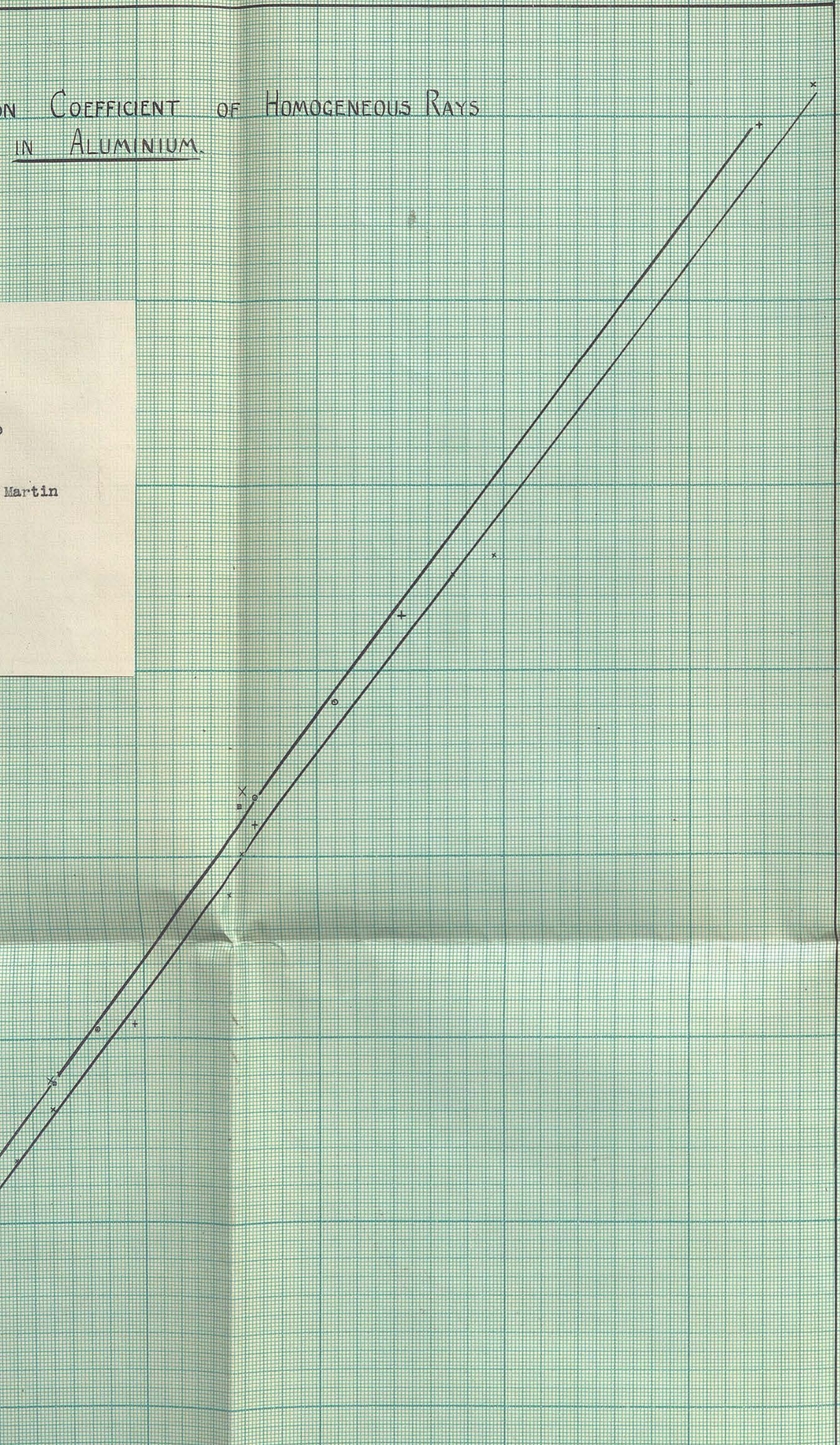
All the experiments described above, therefore, have failed to reveal any evidence of effects of the magnitude to be expected on the grounds which suggested the investigation.

It gives me great pleasure to record here my indebtedness to Professor Barkla for his having suggested this research, and also for his constant helpful criticism throughout the progress of the work.

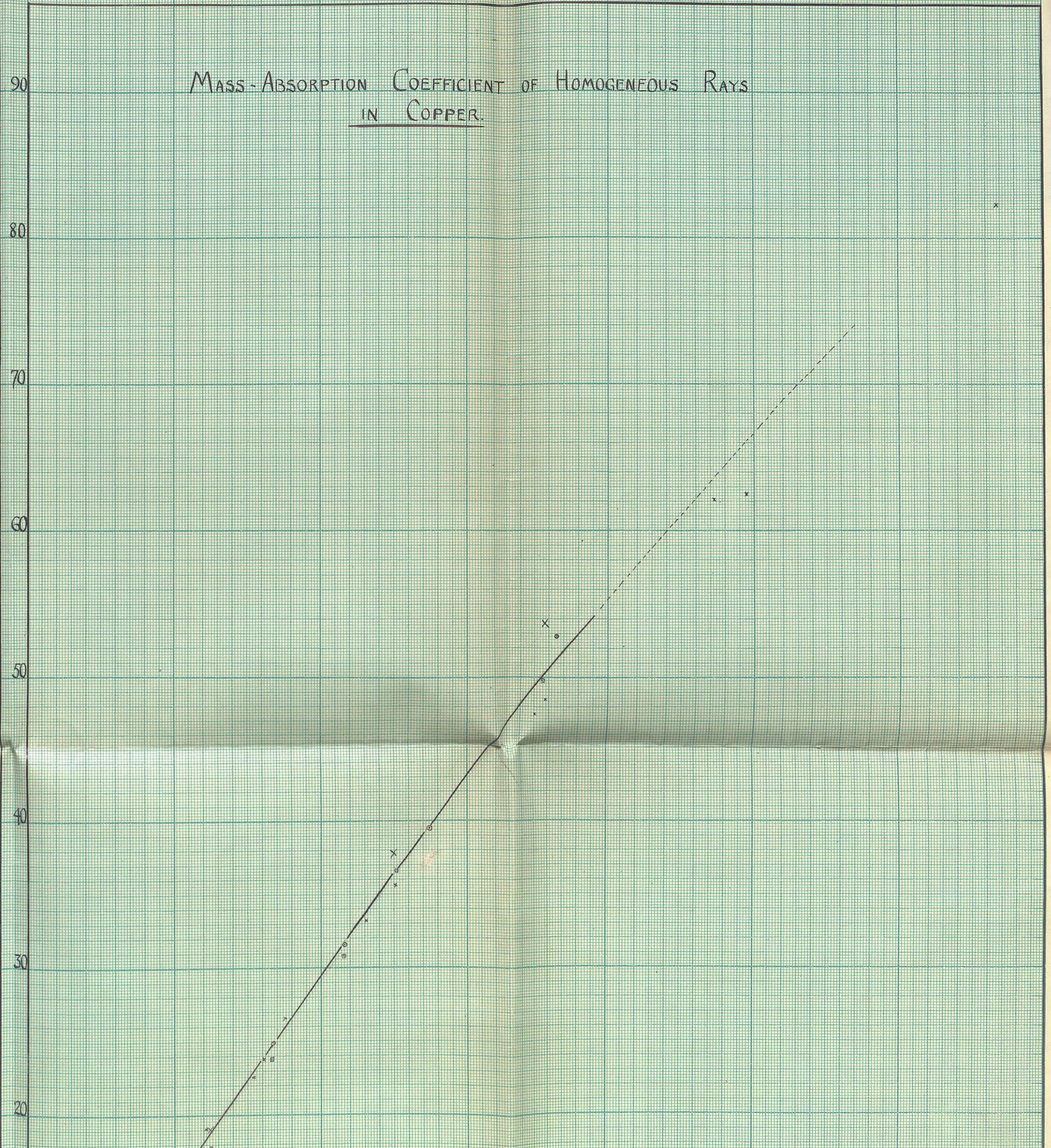
(*Issued separately April* 23, 1925.)


MASS-ABSORPTION COEFFICIENT OF HOMOGENEOUS RAYS
IN ALUMINIUM.
• Hull & Rice
⊙ Richtmyer
⊡ Stoner and Martin
+ Hewlett
× Watson
X Allen
9
8
7
6
5
4
3
2

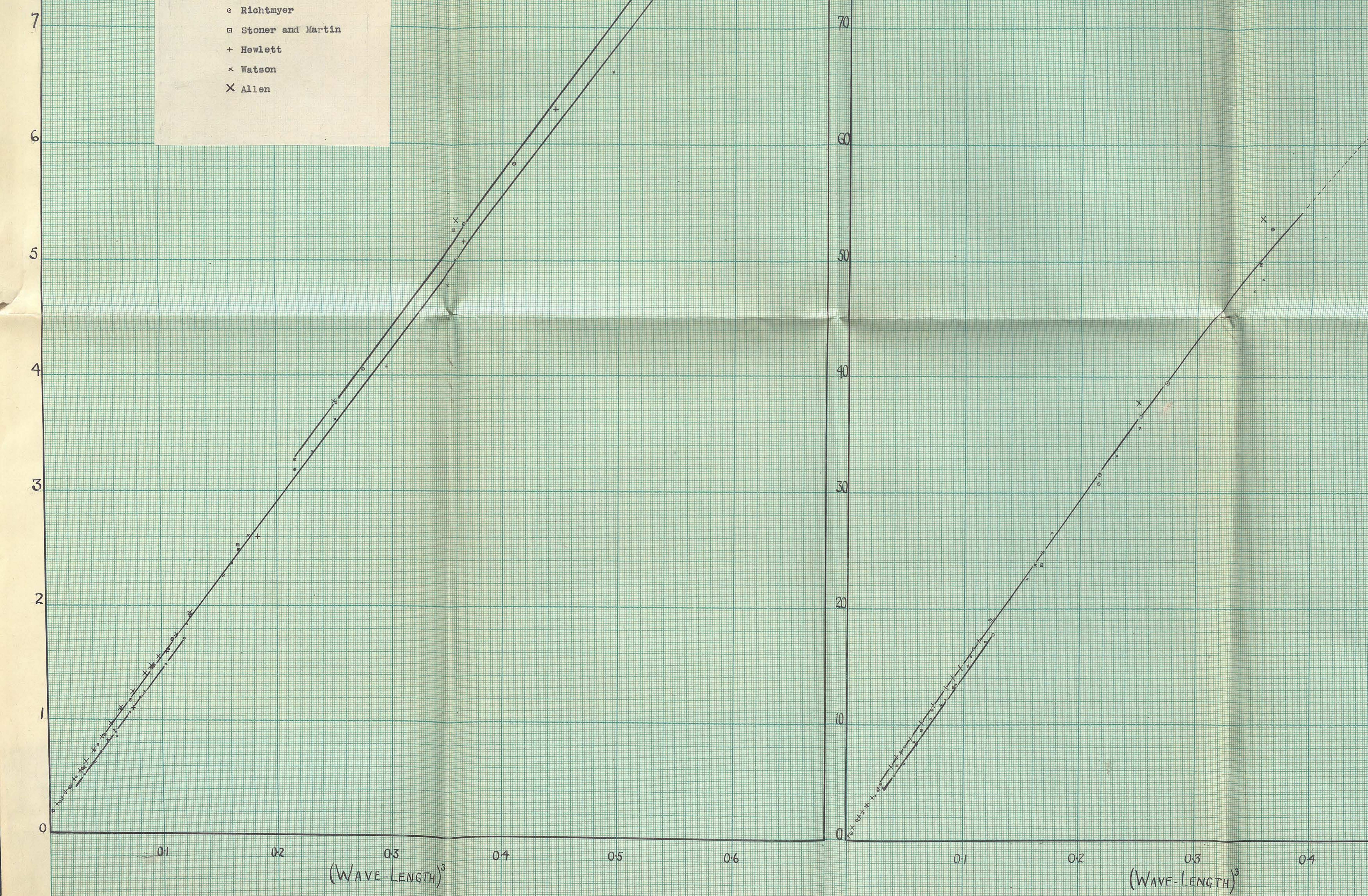

MASS-ABSORPTION COEFFICIENT OF HOMOGENEOUS
IN COPPER.
90
80
70
60
50
40
30
20



...on Coefficient of Homogeneous Rays
in Aluminium.
Martin



Mass-Absorption Coefficient of Homogeneous Rays
in Copper.
90
80
70
60
50
40
30
20



⊙ Richtmyer
⊡ Stoner and Martin
+ Hewlett
× Watson
X Allen
0
1
2
3
4
5
6
7
0·1
0·2
0·3
0·4
0·5
0·6
(Wave-Length)³
0
10
20
30
40
50
60
70
0·1
0·2
0·3
0·4
(Wave-Length)³

Figure II.

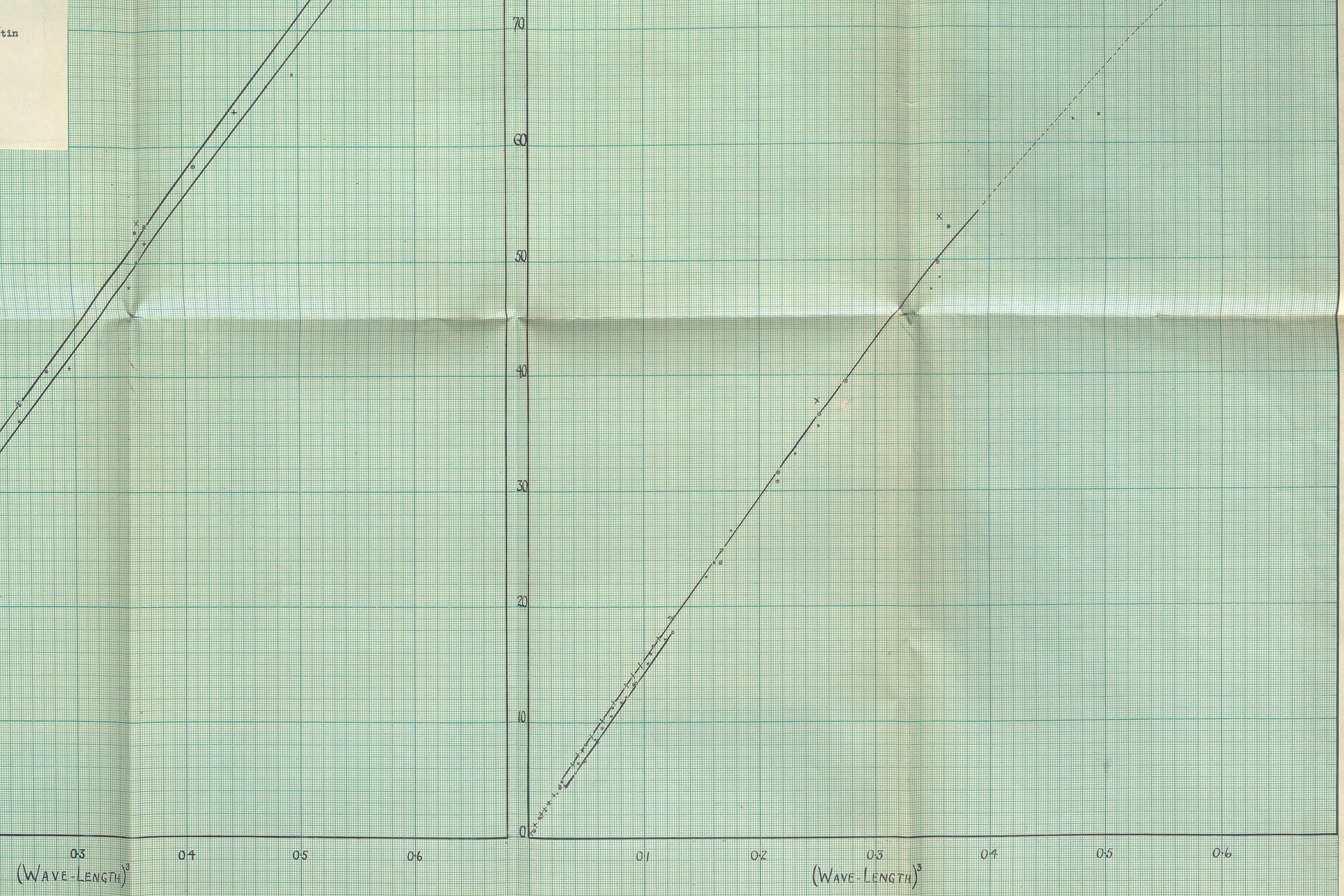

tin
70
60
50
40
30
20
10
0
0·3
0·4
0·5
0·6
(Wave-Length)^3
0·1
0·2
0·3
0·4
0·5
0·6
(Wave-Length)^3

Figure II.